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GDR COAL-DUST LOCOMOTIVE

/Numbers in parentheses refer to appended sources./

I. TECHNICAL DEVELOPMENT OF COAL-DUST-FIRED LOCOMOTIVE

A. Development Before World War II

The idea of building locomotives fired by coal dust is not new. Coal-dust firing was already known at the end of the last century, especially in the United States.(1) [redacted]

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These early coal-dust locomotives could not hold their own in operation because the peculiarities of this method of firing were not yet sufficiently understood, and seemingly insoluble difficulties arose as a consequence. In other countries as well, e.g., Sweden, Hungary, England, The Netherlands, Japan, and Italy, experiments were made with coal-dust firing on locomotives, but they failed to progress beyond the experimental stage for the same reasons. In Germany, during the inflation year 1923, the search for a cheap fuel became imperative and led to the question of coal-dust firing for locomotives.(1) The AEG, Berlin, which by 1918 had built coal-dust firing equipment for stationary boilers, extended its research to locomotive boilers. Simultaneously, in 1923, five other German locomotive-building enterprises, under the leadership of the Henschel Company in Kassel, formed a research association, abbreviated Stug (for Studiengesellschaft), to develop a coal-dust firing method suitable for locomotives.

1. Types of Construction

a. AEG

Towards the end of 1924, the locomotive plant of the AEG in Hennigsdorf near Berlin began construction of coal-dust locomotives. Initially, Series DR 561 locomotive was used; later on, the Series 58 was preferred for conversion to coal-dust firing. The most important changes were as follows:

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Slit burners were installed at both sides of the firebox. [redacted] These burners divided the jets of coal-dust into disks which mix within the firebox with the secondary air and then burn there. The burners were arranged in pairs on the sidewalls of the ashpans and were protected from overheating by circulating water. This type of burner had often been used in stationary installations and thus represented no particular innovation.(1)

Grate and ashpan were replaced by a brick-lined seal-off box.

The tender was converted for coal dust by installing a funnel-shaped coal-dust bunker. The bunker was equipped with two worm conveyors which transported the coal dust forward where it fell into an air canal. A blower-generated draft in this canal then transported the coal dust through a flexible connection to the burners.

Two auxiliary engines were installed on the tender: a turbine to drive the blower, and a steam engine to operate the two worm conveyors. These two auxiliary engines got their steam from the locomotive boiler. Regulating valves permit a choice of the number of revolutions per minute, thus regulating the flow of coal dust and the ratio of coal dust and air. In the front of the bricklined firebox, flaps for secondary air were installed which could be regulated and through which the necessary air for combustion was aspirated by the regular exhaust draught of the locomotive.

The burners were cooled by water, which was circulated by a small steam-driven pump. [redacted] 50X1-HUM

b. Stug

The Stug model used a burner especially designed for locomotives. It was a so-called spray burner, and two of them were placed at the rear of the ashpan.

The spray burner consisted of a conical tube, on the widened front surface of which was mounted a honeycomb-type plate consisting of many orifices. The jet of coal dust, meeting this plate and passing through it, was divided into many small, separate jets. Aside from the great internal resistance of this burner, the distribution of the fuel was also inferior to that achieved by the AEG burner. As in the AEG type, the divided separate jets were mixed in the firebox with the secondary air. In the first version of this model, however, the attempt had been made, by increasing the size of the blower, to induct all the combustion air through the burner along with the coal dust. This version was soon abandoned in favor of inducting additional secondary air through the blower or through the induced draft of the locomotive. It was hoped that in this way the combustion gases could be cooled off sufficiently to prevent the ash particles from being in a pasty or even a liquid state when they left the firebox; for ash particles in this condition after a certain length of time are deposited in the flues and tubes, forming clinkers and thus sharply reducing the performance of the locomotive. To prevent this from happening, efforts were made to have the coal dust as dry and as finely ground as possible.(1)

Furthermore, the Stug model operated with only one auxiliary engine, which drove the blower and the worm conveyors.

The tender was converted in the same manner as on the AEG model. [redacted] 50X1-HUM

The connection between locomotive and tender was maintained by ball joints and packing glands; and, in addition, a number of steam connections had to be provided for starting up with steam from outside the locomotive.(1)

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2. Type of Fuel

It is imperative that the coal dust used be very finely ground. It must not leave more than 20-percent residue on the standard sieve of 4,900 openings per square centimeter. Even finer grinding is preferable to avoid deposits of the back tubesheet. The coal dust should have as little sulphur content as possible because the resulting sulphurous acid quickly eats through the copper fireboxes which formerly were in general use. Only the use of steel fireboxes eliminated this shortcoming. Some of the Central Germany brown coal contains large quantities of sulfur, sometimes more than 7 percent. Thus, the coal to be ground to coal dust had to be selected very carefully. In long-term operations, Michel coal dust from the Michel mine near Halle-Saale had been used.

Coal-dust operation did not prove profitable, because the coal dust was too expensive. Therefore, when, in 1937, the Halle'sche Pfaennerschaft [an old mining corporation] established a new, large, coal-dust grinding mill in Senftenberg (Lausitz) and had to find a large regular account, it offered its coal-dust to the German Reichsbahn at particularly favorable terms and prices. A successful test was made in Halle with Senftenberg coal dust, after which all six Series 58 coal-dust locomotives, which had been stationed in Halle, were transferred to Senftenberg. But it soon became apparent that the new coal dust was not well suited for locomotive operation because of insufficient fineness and its content of brown-coal fibers. After new tests with a dynamometer car, the firing equipment of the locomotives was adapted to the combustion properties of the new coal dust. Thereafter, operations with the Senftenberg coal dust were satisfactory.

3. Operation of Coal-Dust Locomotive

a. Transport and Loading of Coal Dust

The coal dust, which is highly explosive and lumps easily, is transported with compressed air. It then flows somewhat like a liquid. From the grinding mill of the mine it is loaded into special tank cars. From these it is transferred to the bunkers of the locomotive tenders. The compressed air used for the transfer is released into the open through filters on the bunkers. These cloth filters get clogged very quickly and occasionally they tear and clouds of coal dust escape.

The German Reichsbahn never had stationary coal-dust bunkers. Instead, its coal-dust locomotives were filled from the tank cars, and later on, in Senftenberg, the coal dust was transferred directly from the grinding mill of the mine to the locomotive tenders.

b. Firing Up

To fire up a coal-dust locomotive, a wood fire is started in the firebox. The auxiliary machines are then started with outside steam, e.g., from another locomotive, and coal dust is then blown in. It is possible to get pressure in a comparatively short time (one hour) but such quick firing up is usually avoided on account of the tensile stresses in the boiler plates.

After the proper boiler pressure has been reached, the locomotive is ready for service. Locomotive operations must be scheduled in such a manner as to bring the locomotive to its supply of coal dust before the supply carried in the tender is exhausted. The supply point must be equipped with a compressed-air installation.

c. Locomotive Operation En Route

The duties of the fireman en route are limited to adapting the number of revolutions of the worm conveyors to the coal-dust demand of the fire and adjusting the input of primary air by regulating the blower. The secondary air is induced automatically in proper quantity by the action of the exhaust nozzle. The experienced fireman knows by the movements of the boiler pressure gauge and by the color of the smoke leaving the smokestack how he must operate the auxiliary machines. The fireman of the coal-dust-fired locomotive is spared the arduous task of stoking coal.

Gray ashes are constantly being expelled from the smokestack and are distributed evenly over the surrounding area. The combustion gases have a sour odor because of their content of sulfurous acid. This odor and the rain of ashes impair the locomotive's suitability for passenger traffic. Therefore, only freight locomotives had been converted to coal-dust firing.

During prolonged periods of idleness of the locomotive, the burners are doused. Originally the locomotives had special small burners for such periods, but in later practice these were ignored in favor of a wood fire. The wood ignited spontaneously on the hot brick lining.

d. Performance of Coal-Dust Locomotive

Prolonged tests in the former testing division of the Reichsbahn succeeded in raising the boiler performance of a coal-dust-fired locomotive to that of a black-coal, grate-fired locomotive. The German Reichsbahn considers an evaporative capacity of 60 kilograms per square meter of heating surface per hour as "full." This high load was actually reached with either type of firing. However, after prolonged operation, deposits of ashes and unburned coal dust accumulated gradually on the back tubesheet and in the tubes and flues, making effective long-term boiler operation impossible. Yet, the locomotives were definitely efficient.

The coal-dust bunkers of the locomotives hold about 9 tons of coal dust. That is sufficient to convert more than 35 cubic meters of water into steam. This determines the effective radius of action of the locomotive. It is estimated that in normal train operation one cubic meter of water is needed for every 10 kilometers of running distance. On that basis, these coal-dust locomotives could run a maximum of 350 kilometers without refueling. Mountainous terrain of course requires more fuel and the radius of action of a coal-dust locomotive in mountainous territory is correspondingly smaller.

Until 1930, six locomotives of the Series 58 and four of the Series 56 had been converted to coal-dust firing, half of them by AEG, half by Stug.(1) After many months of tests with the dynamometer car of the German Reichsbahn, these ten locomotives were turned over to the Reichsbahn Directorate Halle. There they operated faultlessly, except for the necessity of frequent cleaning of the flues and tubes and the rapid deterioration of the firebox plates. After the latter had been replaced with steel plates, the locomotives operated rather satisfactorily.

The coal-dust locomotives were chiefly used in the transport of heavy brown-coal briquette trains to Berlin and of the empty return trains of Senftenberg.

The coal-dust locomotives operated without any major difficulties until the first years of World War II, partly from Halle, partly from Senftenberg. But then they gradually lost their importance because they were less suitable as war transports since they depended on a specific fuel base.

 [redacted]

B. Postwar Development

When Germany was occupied, the Soviets dismantled the modern brown-coal-dust plant in Senftenberg. Black coal is practically nonexistent in the German Democratic Republic. [redacted] Thus, locomotives had to be fired with brown-coal briquettes. This caused a marked reduction in operating economy, not to mention the other unpleasant features that this method of firing involved. The coal industry and others concerned urged repeatedly that the question of firing locomotives with coal dust be again seriously considered.

But there were seemingly insoluble problems in the way. It was no longer possible to obtain the dry and finely ground coal dust that had formerly been used; besides, at most, ten coal-dust-fired locomotives would have been available, an insignificant number. As a result of the war, the coal-dust locomotives, for some time out of service, and especially their auxiliary equipment, had been badly damaged. It was impossible to obtain substitute equipment or spare parts. Eminent experts dismissed as an impossible assignment the request of the Coal Dust Administration for coal-dust firing.(1)

In the process of hiring politically untainted persons, the Berlin civil engineer Hans Wendler was hired by the German Reichsbahn. He had worked with coal-dust-firing equipment for stationary boilers at the KSG (Kohlenscheidungsgesellschaft, Coal Refining Company) [redacted] In 1948, Wendler /at present chief referent of the Directorate General of the Reichsbahn7 approached the directorate general and asked permission to construct coal-dust-fired locomotives. Schramm, then deputy director general, and particularly Kramer, then chief of the mechanical department and now director general, gave him every possible encouragement and support.

Wendler took a locomotive of the old Stug model and put it into condition to try out the available coal from the Geisel Valley. The burner of the Stug model and the arrangement of the firing showed that the coal available could not be used this way. This conclusion confirmed the previous experience with coal-dust firing on the 05 003 fast locomotive. The conditions of the rule for high-output firing formulated by Wendler were then met by hermetically closing the combustion space and the flues and tubes against the outer atmosphere. With that, the total air of combustion was forced to pass through the burner, and its volume was always properly measured at all rates of fuel feed; it was also mixed with the fuel before it entered the zone of combustion. It was thus possible, after installation of a vortex burner designed by Wendler, to make economic use even of the /inferior7 coal-dust available. /Construction of this passage in Germany is ambiguous. It may also mean: If the fuel was mixed with air before entering the zone of combustion and if a vortex burner designed by Wendler was installed, then it was possible to make economic use even of the coal-dust available.7

Whatever secondary air might still be required could be automatically aspirated through a built-in jet system, according to the locomotive load at any given moment. After these favorable experimental results had been obtained, repairs on this locomotive were immediately commenced and further development pushed ahead. Before everything else, a very wide variety of coal had to be studied by means of careful and detailed trial trips. Salt coal f[illegible]he Geisel Valley, in particular, was the subject of a fairly long test pe[illegible]. Some of this coal was so damp and so coarse that it could not be handled by the worm conveyor; the auxiliary engine stopped pulling or the worm became completely stuck. After completion of these experiments, the locomotives, which had been made ready in the meantime, were placed in regular scheduled service in the beginning of 1949.

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From the point of view of combustion engineering, these locomotives, which were equipped with auxiliary steam engines, turbines, worm conveyors, couplings, blowers, etc., functioned perfectly with the firing equipment designed by Wendler. They were not particularly popular from the operating standpoint, however, because of the constant attention required by all the auxiliary machinery. A continuous supply of spare parts was not assured and the equipment needed constant maintenance The Wendler group realized that rebuilding whatever locomotives there were would not be of very much use from the economic viewpoint, and that it would not even have been possible to build locomotives with the old method of fuel delivery, since the auxiliary machinery would still have been unobtainable. For this reason, they selected a locomotive of the Series 58 1353, which was on hand, took out the entire complicated delivery mechanism with its three-cylinder steam motor, worm conveyors, couplings, vortical devices, etc., and tried a pneumatic method of delivery. This was designed to apply compressed air at a pressure up to 0.5 atmospheres absolute pressure (normal 0.2 to 0.3 atmospheres absolute pressure) to the coal dust, which would then be forced through built-in orifices, after a special delivery valve had been constructed from the old valve. After initial difficulties, this method of reconstruction was completely successful, and it thus became possible to build coal-dust firing locomotives, since, with the exception of the turbo-blower, no other complicated parts were required. The locomotive pulled every type of train without difficulties and very soon its simplicity made it popular among the service crews.

Thereupon director general Kramer gave Wendler the assignment, at the beginning of 1949, of rebuilding an express train locomotive, Model S 10[1] (17), for coal-dust firing and of equipping it with a condenser-tender at the same time. This problem was very hard to solve, for this tender holds a condenser turbine, piping, etc., so that it was quite difficult to find room for a fairly large amount of coal dust, to say nothing of the turbo-blower that had been required, up to that time, for coal-dust firing. For this reason it was attempted to dispense with a turbo-blower for the first time in the history of coal-dust technology, by aspirating the entire air of combustion over the burner by means of the induced-draft aspirator with which the smokebox of the condenser-locomotive is equipped. The amount of coal dust corresponding to the load at any given moment is then added pneumatically to this induced air stream. By this very daring step, which led to complete success, the coal-dust locomotive became so simplified that it no longer had any mechanically actuated moving parts. The connection between locomotive and tender was no longer by means of a ball joint of cast steel and a stuffing box; these could now be replaced by simple rubber hose. This rubber hose has given excellent results and has now been installed on all coal-dust firing locomotives. The steam connections between locomotive and tender, too, are now made by means of bent tubing similar in form and action to a safety pin, which has now been installed on all locomotives.

The path had now been cleared for the remodeling, in series, of locomotives for coal-dust firing. Wendler received the order to begin construction of higher-capacity tenders for G-12 (58) locomotives. He used four T 31.5 tenders with lattice-work trucks of the old Prussian model, equipped them with four fuel delivery units, and was able to load them with up to 16 tons of coal dust and about 24 cubic meters of water. With the type of worm conveyor formerly used, it had been necessary to keep the normal auxiliary blower going while the locomotive was standing or running under reduced load, in order to aspirate the combustion gases; this blower was now fitted with special jets which opened directly into the smokestack of the locomotive, and achieved a considerable increase in performance with the same steam consumption. In any case, this auxiliary blower worked well enough to allow the builders to dispense with the blower, just as had been done with the condenser-locomotive. A Bulgarian locomotive was also remodeled according to the same principles for the People's Republic of Bulgaria, and it can now burn low-grade Bulgarian coal. This locomotive corresponds to the East-German Model 50 and it is now operating to fullest satisfaction in Bulgaria. At the same time, Wendler undertook the remodeling of other S 101 locomotives without condenser equipment and these are at present operating without difficulty even on black-coal dust.

At the present moment, tests are under way with a so-called pneumatic chamber-delivery. If this method of delivery proves acceptable, only two delivery valves will be required for the coal dust; the tender design will thus be substantially simplified, and more supplies can be carried. With this arrangement of the delivery method, the problem of design for cars to carry coal dust also seems to be solved, for any tank car would be suitable for transporting coal dust after only slight remodeling. A refueling connection is attached to every tender of coal-dust locomotives, and this makes it possible to transfer coal dust to the tender, while under way, from a fuel car carried along in the train, thus giving a coal-dust locomotive a practically unlimited radius of action.

The superiority of the coal-dust locomotive over the ordinary grate-fired locomotive has been shown by the results of a number of test trips which were carried out from the very beginning. Among the many advantages of coal-dust firing are the following: there is no shortage of steam; flying sparks are completely eliminated, as well as ash-dumping under way, which soils the roadbead; there is no more smoke, and fuel combustion is almost complete, thus assuring extreme cleanliness in operation so that the passengers may open the windows even while the train is running; the same locomotive can be used for trips of any distance; it normally takes about 45 minutes to get up steam, compared with 4-6 hours for a grate-fired locomotive; cleaning the smokebox, grates, and ashpan is practically eliminated; coaling is cleaner and quicker; above all, the working man on the locomotive is completely freed from his hard physical labor and is released to share observation of the track, thus enhancing safety of operation; it is much cleaner in the cab than in those of grate-fired locomotives, and cars will be changed less frequently because of the cleaner operation. But besides all this, considerable quantities of coal are saved.

Coal-dust consumption ranges from 30 to 36 tons per million locomotive-ton-kilometers for trains which are not always fully loaded and on single-track lines where frequent stops and starts are necessary. For fully loaded trains, heavy freight trains, and on double-track lines on which trains do not stop so often, this figure is between 26 to 29 tons. The trial runs with the dynamometer car in November 1950 demonstrated conclusively that there were enormous savings as compared with the grate-fired locomotive. Pulling the dynamometer car, the savings were about 40 percent. In practical operation, a saving of 30 percent can be anticipated if all the technical conditions are assured and the corresponding equipment used.

One third of the entire East-German coal production goes to the Reichsbahn for the fulfillment of its transportation tasks. If we figure the consumption of coal dust at 40 tons per million locomotive-ton-kilometers, this would mean an annual saving of more than 8 million tons of briquettes, if 1,250 locomotives were fired by this method.

/Wendler sums up the situation as follows:7

The great economic significance of a readjustment of our locomotive operation to coal-dust firing can be clearly recognized from these data, which are not exaggerated. The authorities of the German Democratic Republic are interested, after these successes, in taking advantage of this possibility of saving coal and in fully utilizing it within the framework of the Five Year Plan.(1)

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/Another source, however. takes the following view:7

Lately, there has been a shortage of suitable coal-dust because it was found that, as heretofore, only coal-dust with a maximum residue of 20 percent on the 4,900 sieve is actually usable. Such coal-dust is in short supply in the Halle area, and Senftenberg has not resumed deliveries yet. Therefore, plans are being voiced to reconvert part of the coal-dust locomotives to grate-firing. Furthermore, the high sulfur content of the brown-coal dust always creates difficulties. Those copper fireboxes still in existence are almost corroded through, and steel fireboxes cannot be manufactured in the German Democratic Republic as yet. Thus, several boilers have torn open already, an occurrence which always constitutes considerable danger for everybody in the vicinity. [redacted]

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II. THERMAL ASPECTS OF COAL-DUST-FIRED LOCOMOTIVE

/This entire section is taken from Scurce 3.7

(German editor's note: Fritz Selbmann, Minister for Heavy Industry, explained in detail at the coal conservation conference in January 1951 that the utmost economy in the use of solid duels is necessary in order to fulfill the Five-Year Plan. The 1951 law concerning the National Economic Plan imposes on every consumer the obligation of economical use of fuels. This law also requires the widespread substitution of brown coal for black coal. The Reichsbahn, which is the largest consumer of fuel in the German Democratic Republic, has made successful efforts, during recent years, to reduce its coal consumption. The use of coal-dust-fired locomotives by the Reichsbahn is a further step towards reducing fuel consumption. As the coal-dust locomotives currently in operation are still not satisfactory regarding the amount of fuel consumed, it is considered necessary to examine more closely the thermal conditions required in the firing of coal dust in locomotives.)

In spite of the fact that the problem of burning brown-coal dust had been solved in both the AEG and the Stug (Studiengesellschaft) models before World War II, the coal-dust locomotive was unable to win extensive acceptance. The number in operation remained limited to the ten that had been in use for about 15 years in the brown-coal mining area, and had given good results there. Because of better utilization of the heat content of fine-grained coal dust, their thermal efficiency was about 20 percent higher than that of the fire-grate locomotives burning black coal. The savings in fuel costs were sufficient to cover amply the high capital investment needed for the auxiliary equipment. The price of coal dust, corresponding to its lower calorific heating value, was 11 Deutsche marks per ton fob plant, with the price of black coal at 16 Deutsche marks per ton. After the war, however, conditions were entirely different. No black coal is now available for use by the Reichsbahn, and even if Ruhr coal could be obtained for the locomotives, its price has doubled. The price for brown-coal dust has remained unchanged; even if the Reichsbahn were to grind chips or dry coal in its own mills, the cost of coal dust at 16 to 17 DM (Deutsche marks) per ton would still be lower per unit of heat than that of black coal: using brown-coal dust, 1 x 10^6 kilogram-calories cost about 3.40 DM: using black coal, 1 x 10^6 kilogram-calories cost about 5.10 DM.

Although the cost of briquettes per unit of heat is about the same as that of brown-coal dust, the consumption of briquettes is substantially higher in operation.

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Even if fine-grain briquettes, with a price corresponding to 4 DM for 1×10^6 kilogram-calories, are used, the consumption is still 10 to 12 percent higher than with coal-dust firing in standard equipment, so that fuel consumption and fuel costs will be as follows:

	Consumption	Cost
Standard briquettes	1*	1*
Fine-grain briquettes	0.3	0.95
Brown-coal dust	0.7	0.7

* Standard briquettes taken as 1

It is clear from this comparison how very important an increase in the number of coal-dust locomotives will be, not only to the Reichsbahn, but also to the entire national economy. The addition of only 200 such locomotives will release about 500,000 tons of brown-coal briquettes a year for other consumers and will only require, in their place, 350,000 tons of coal dust, which can be produced from the residue of briquette stamping and from the slack by other large consumers.

The existing locomotives were constructed to burn black coal, and the dimensions of their combustion space are figured accordingly. Because the gas content of black coal is low (from 30 to 35 percent) it produces a shorter flame than brown coal with its 45 to 50 percent gas content. When burning black coal, only the tips of the flame go above the brick arch; and no more heat is developed in the upper part of the firebox, so that the temperature of the combustion gases is reduced by radiation. At the back tubesheet, as the gases enter the contact heating area, the temperature of the flying ash particles carried along with the gases has already fallen below the softening point. This is not the case with brown coal, which has a long flame. The flying coke particles have not completely burned at the back tubesheet and are forced through the tubes so that they begin to glow brightly as soon as they come in contact with the oxygen of the air above the smokestack. This is the cause of the rain of sparks when brown-coal briquettes are fired. It illustrates clearly the wastefulness of firing brown-coal briquettes.

Coal-dust firing must be adjusted to the conditions in the combustion space and must be developed accordingly. The volume of the combustion space is only about 6 cubic meters. Within this space and given a maximum boiler load of 57 kilograms per square meter per hour corresponding to the generation of 12 tons of steam, 2.4 tons per hour of coal dust must be burned. With a calorific heating value of 4,800 kilogram-calories per kilogram, there is thus a heat transfer of 1,900,000 kilogram-calories per hour per cubic meter of combustion space. This is an exceedingly high figure, compared to stationary boilers fired by coal dust, which are usually operated at only 250,000 kilogram-calories per square meter per hour, in order to reduce clinkering of the heating surfaces. The flame path is therefore held to 10 to 15 meters in length, which must be traversed by the hot gases before entering the contact heating area. In spite of the particularly unfavorable conditions in the combustion space, both the AEG and the Stug models mentioned above were successful, after initial difficulties, in preventing clinkering on the back tubesheet or in reducing it to minimal proportions. Comprehensive technical and scientific research was required to ascertain the causes of the clinkering and to eliminate them.

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In firing coal dust on locomotives, the same rules, in principle, are applicable as for stationary installations. Clinkers on the back tubesheets of locomotives are equivalent to clinkers at the entrance to the contact heating area of stationary boilers. Both are the result of poor combustion due to inadequate mixture of coal dust and combustion air because the flame path is too short, and thus the hot gases and flying cinders are insufficiently cooled, so that the temperature of the flying cinders remains above the softening point of the ash.

The primary demand of locomotive firing is the conduction of the flame over the longest possible path, which is an S shaped flame

Such a flame makes complete utilization of the combustion space possible. This determines the nature of the burner, which must allow the mixture of coal dust and air to be emitted as a directed stream. Built-in swirl-generating surfaces can only serve to favor the turbulence of the mixture. An S-flame cannot be obtained with a vertical burner, for it is in contradiction to the purpose of such a burner, which is designed to impart a strong swirling motion to the mixture and to cause it to enter the combustion space in widely dispersed form. But a firm conduction of the flame in an S-form is only possible if the mixture of coal dust and air is injected under pressure into the combustion space, for only in this manner can the dust particles take the desired path. The S-flame cannot be obtained by induced draft, that is, when the fuel-air mixture is induced into the combustion space by suction through the feed pipes, since in this way the fuel particles are sucked away from the burner by the shortest path over the brick arch, and with continually increasing velocity. The flow thus follows the vacuum inside the firebox, which increases continuously from the burner to the back tubesheet. The path of the fuel particle, and thus of the flame, can be precisely calculated by the Bernoulli equation of flow, if the static pressure at a number of points in the combustion space is known by measurement. In an unpublished 1931 paper, the past master of coal-dust firing, Professor Rosin, recorded detailed measurements and thoughts on this question of the flow conditions within the combustion space. The following are the essential points.

Professor Rosin writes on the conduction of the flame:

"To 'conduct a flame' means to force it into as stable and expedient a form as possible, by influencing its direction and dimensions. Of the many problems arising in the connection, we shall select only two which are of particular significance for coal-dust locomotives. These are the questions of the injection velocities of primary air and coal-dust, and of the double reversal in the flame resulting from the shape of the combustion space.

"By constricting the cross section of the burner plate, the primary air and the coal dust are highly accelerated; the resultant forces are directed horizontally and tend to counteract the upward draft. But, from the burner plate, the available cross-sectional areas in the combustion space broaden out very rapidly, so that the jet would be strongly retarded if the expansion in volume that results from combustion did not compensate for this. If ignition is sluggish, the velocity must fall; this leads inevitably to a straightening out of the flame, that is, to very poor filling of the combustion space. With fuels having a tendency to fuse, the deposition of coke is an additional factor that materially aggravates this situation, because the sudden drop in velocity during ignition causes the coal dust to separate abruptly and to coke upon the hot surfaces. The condition of the flame deteriorates more and more in this manner, for the horizontal forces reach their minimum just at the point where the vertical forces of draft and uplift are great.

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"If, on the contrary, there is spontaneous ignition behind the burner plate, then the flame maintains its full velocity in the direction of injection. How much of this velocity still remains after the ignition obviously depends on the primary injection velocity and on the acceleration of the ignition process. These two factors are by no means independent of each other. Ignition is furthered by the marginal effects of the burner plate and by the burble of the vortices behind it. The degree of vorticity with a given burner plate depends entirely on the entrance velocity; on the other hand, the ignition path is lengthened by an increase in the velocity of the gas, if the time of ignition remains unchanged, which factor tends to counteract the favorable influence of increased vorticity. Accordingly, there exists an optimum injection velocity that assures the shortest ignition.

"Since this demand of combustion engineering is absolutely categorical, the injection velocity cannot by any means be chosen at will. To attain good flame conduction, all means of shortening the ignition time such as, above all, the adjustment of the quantity of primary air, must be so strongly intensified that the aerodynamically necessary gas velocity becomes permissible; for the induction of secondary air, and thereby the problem of clinker formation stands and falls with a tight conduction of the flame. This tight conduction does not of itself follow from the mere position of the boundary walls. As has already been repeatedly indicated, the flame has by no means a natural tendency to reverse itself twice and then to head for the back tubesheet; it seeks rather, like all gas streams, to escape upwards from the burner by the shortest way over the brick arch, like a thread that always takes the form of a straight line when subjected to tension and can only be brought out of this position by separate lateral components. It follows from this that the flame has a certain liability; it does not press itself close against the walls, but reacts to every change in the aerodynamic forces by a corresponding deformation.

"This does not necessarily imply that such a flame arbitrarily seeks paths that cannot be followed and explained; it means rather that the equilibrium is dynamic and can be maintained only by precise regulation of the participating forces. The difference between this and an absolutely stable flame is shown by the example of a flame-tube boiler, in which the position of the central streamline necessarily and unchangeably remains a straight line in all cases. The question as to the conditions assuring the desired S-shaped flame is, therefore, important. It may be best answered with the aid of the velocity diagram of a flame so conducted."

Professor Rosin then represents the gas velocity along the flame path of an average streamline. Typical is the high gas velocity up to the first reversal of direction, and the considerably lower velocity on the return way, and which then remains approximately constant until its arrival at the back tubesheet. This velocity distribution is what really holds the key to flame conduction. It is fundamentally true for any flow at all that it only follows the fall in the static pressure. The velocity values play no primary role whatsoever in the direction of the stream; only the differences in static pressure do.

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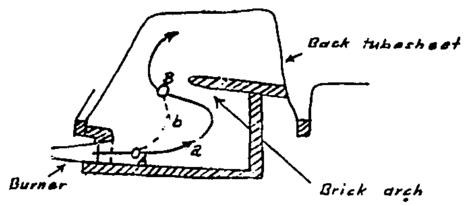

Figure 1. Pressure Distribution and Gas Path

Thus, if no gas is to flow from A to B along the broken line b in the schematic sketch of a streamline in Figure 1, the only condition for this is that the static pressure at B must be a least equal to that at A. According to Bernoulli's Law, the sum of the static and dynamic pressure, as well as the frictional losses along a streamline, must be constant. This would also have to apply to the points A and B, that is:

$$p_A + \frac{w_A^2}{2g}\gamma = p_B + \frac{w_B^2}{2g}\gamma + \Delta p$$

p is the static pressure in millimeters of water

w is the gas velocity in meters per second

g is the acceleration of gravity in meters per second

γ is the density of the gas in kilograms per cubic meter

Δp is the frictional loss of pressure between A and B in millimeters of water

$p_A \leqq p_3$ only if

$$\frac{w_A^2}{2g}\gamma_A \geqq \frac{w_B^2}{2g}\gamma_B + \Delta p$$

If we assume that $\gamma_A = \gamma_B$, i.e. that $T_A = T_B$, it follows that

$$w_B \leqq \sqrt{w_A^2 - 2g\frac{\Delta\gamma}{\gamma}}$$

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In other words, the gas velocity must decrease by a very definite amount, corresponding to the frictional of pressure, with a compensating increase in the static pressure. This is in fact the case.

With a locomotive operating under the induced draft system, however, the static pressure measured at A was 120 millimeters of vacuum, while at B it was 150 millimeters of vacuum, so that the requirements established by Professor Rosin cannot be met in this case. It follows clearly from these considerations that the higher the injection velocity and the greater the space available for the flame reversal, the firmer and the more stable the flame conduction will be.

In deciding whether equipment to fire coal dust should be designed for induced draft or forced draft, these considerations adduced by Rosin cannot be ignored. A flame path about 5.50 meters long can be attained by the use of the force draft or injection principle, while under induced draft its length is 3.50 meters at most. This difference alone reduces the stay of the fuel particles in the combustion zone by 26 percent when the latter method is employed.

As a second requirement, we must try to attain a rapid completion of combustion, with high initial temperatures. By the time it reaches the tip of the brick arch, that is, after traversing an S-shaped flame path about 4 meters long, the flame should have completed its combustion. This is necessary so that, before the combustion gases enter the flues and tubes, they will have cooled of by transfer of heat to the radiation heating surfaces in the upper part of the firebox above the brick arch; the cooling must be enough to bring their temperature below the softening point of the lowest-melting eutectic. In designing the firing equipment, therefore, the basic point to be considered must be the melting behavior of the ash from the coal dust to be fired. The softening point of coal dust from the Central German mining area, which is the primary source for locomotive fuel, is as low as 850 degrees centigrade, and in a few scattered exceptions even 750 degrees. Salt coal, with its consistently low softening points, is thus unsuitable for locomotive firing. Coal with salt content under 8 percent of Na_2O in the ash is fired in stationary boiler installations with long flame paths; but in experiments with a coal-dust locomotive, an Na_2O content of only 4 percent in the ash was sufficient to coat the inside of the flues and tubes with a thick crust of salt and flue dust after only 75 minutes. Brown-coal dust, even from the very same mine, under goes sharp fluctuations in the course of time.

These fluctuations are inherent in coal and cannot be avoided. Equipment to fire coal dust must, therefore, be adapted to these conditions; it must be so designed that with the full boiler load the temperature of the combustion gases has at least dropped to the softening point of the dust ash by the time it reaches the back tubesheet. For this reason, a cool-air device should be provided so that cool air can be added shortly before the gas arrives at the back tubesheet, in cases where the ash has a low softening point. Compressed air should be used to provide sufficient cooling for the entire cross section of the gas stream. Moreover, it is essential to the rapid completion of combustion that the fuel should not be too coarse-grained. In prewar operation, it proved advantageous to use coal dust that left a residue of 20 percent on the DIN 70 test sieve with 4,900 meshes to the square centimeter. The velocity of combustion depends on the total surface exposed, which increases with the degree of fineness of the dust.

Test runs were made with a locomotive firing coarse-grained coal dust, and the result described it as usable. Unfortunately, exact quantitative data are unavailable. The fact that such coarse-grained fuel could be made to burn at all in the locomotive firing equipment was substantially because of its high bitumen content and its tar content of over 18 percent. Presumably, its volatile components and tar vapors were substantially included

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in the substances burned. It is also important that the residue on the sieve with 900 meshes per square centimeter should not exceed a few percent; but this portion is fixed by the easily adjustable constant with the 4,900-mesh sieve. There is a correlation between screen size and amount of residue left on a particular screen. If a plot is made of amount of residue (expressed as percent of total sample) on a screen versus screen size (i.e., number of meshes per square centimeter), then the resulting curve is found to be exponential.

The water content of the coal dust should not exceed 16 percent. Before the war, 12 to 14 percent was the required figure, and this should again be our objective today. The water content, however, affects combustion only slightly by changing the calorific heating value. Its effect on handling and stoking is more serious. If the water content exceeds 16 percent, the danger of bridge formation inside the tender arises. When the fuel is stoked by a screw-conveyor stoker, it easily briquettes inside the stoker. It is also important in this connection that the fuel compartment of the tender should be insulated from the water tank. In general, the coal dust is passed into the tender by compressed air. The moisture of the air enters the fuel compartment together with the compressed air, and, unless this compartment is insulated, this moisture will condense on the surface of contact with the water tank and will form water concentrations there that can easily lead to bridge formation.

In locomotive firing, the stoking should be assured and uniform. This assumes the uniform introduction of fuel and air in the proper ratio. This aim was attained in the Stug locomotives by a joint drive mechanism of blowers and screw-conveyer stokers. If the stoking does not proceed uniformly and with correct amounts of fuel, backfiring results in the firebox, and can extend back into the fuel feed pipes. If these pipes are open at the rear end, as they must be for induced draft, there is even the danger that the cars following may catch fire.

It was mentioned at the beginning that the second requirement is for high initial temperatures and a short flame; careful adjustment of air intake is necessary to achieve this. The highest temperature and shortest combustion time will be obtained from the exact apportionment of the air of combustion in proper sequence. Fuel and air must mix at precisely the right moment. The gas stream inside the firebox must be thought of as divided into separate strands, which require a definite path up to their complete mixing. The finer the subdivision produced by intensive mixing, the shorter the path to mixture and complete combustion. The hotter the flame at the beginning, with the same CO_2 content at the end of a given heating area, the greater the total amount of heat transferred and the lower, therefore, the final combustion gas temperature will be.

This increase of initial flame temperature may be obtained by corresponding adjustment of the combustion-air intake. This was correctly recognized in designing the prewar coal-dust-fired locomotives. The total air of combustion should not be introduced before the burners, but only that portion which is required for rapid combustion of the volatile constituents. For this reason, the primary air should not exceed 50 percent if brown-coal dust of about 45 percent volatile content is used; and with black-coal dust it must be even lower. The rest of the air required for combustion should then be introduced as secondary air, at a later stage of the combustion. In this way, we obtain the shortest flames and thereby the most rapid completion of combustion, which should be completed in coal-dust locomotives by the time the flame reaches the end of the brick arch. In stationary installations (for instance, with "Kraemermuehlen" firing, which generally uses little secondary air), longer flames are always observed than with other coal-dust-firing equipment.

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If all the air of combustion is introduced through the burners as primary air, there will be an excess of air during the initial stages of combustion, which reduces the temperature of the flame and thus retards combustion. This excess air mixes with the combustible components later in the course of the flame, as a result of the combustion turbulence, and thus a long flame is produced, which, in coal-dust locomotives, extends far beyond the brick arch and up to the back tubesheet. Since the increase in the flame temperature reduces the cooling of the combustion gases by the heating surfaces, a sufficiently low temperature of the combustion gases at the back tubesheet cannot be attained by this method. In consequence, clinkers appear on the back tubesheet, belated combustion occurs in the flues and tubes, and a great quantity of unburnt particles leaves through the smokestack as gases and coke particles. Thus, the air of combustion exclusively in the form of primary air also affects the efficiency of the firing process.

Under induced draft, the entire air of combustion is sucked through the fuel feed pipes into the firebox by the vacuum produced in the smokebox by the exhaust nozzle, thus making it impossible to meet the basic requirements of coal-dust firing, which are high initial flame temperature and rapid cooling of the combustion gases. But these same requirements are basic for every firing installation, whether it is a coal-dust locomotive or a stationary boiler; they should be incorporated in the design of all firing equipment. This is the only way to prevent the dreaded formation of clinkers on the heating surfaces. Even saliferous brown coal, so disliked and avoided by combustion engineers, may be freely burned without objection in any firing equipment whose design complies with these basic requirements. The justification of these requirements has been demonstrated in detail by the experience with saliferous brown coal burned in an experimental boiler in the Central German mining district. These requirements are for complete combustion of both carbon and sulfides before the contact heating surfaces, and for the cooling of the combustion gases below the softening point of the ash by the time these surfaces are reached. With given values for volume of combustion space and area of heating surfaces, they can be met only by a better mixture of coal dust and air while preventing strand-formation by improving heat transfer, which means high initial temperature and short time of total combustion. Under certain circumstances, cooling air must be admitted in the form of tertiary air to the locomotive firebox, which is an especially difficult location.

It follows from the above that only a part of the air of combustion should be injected as primary air into the firebox along with the coal dust, and that the secondary air must be added at the proper place, that is, still below the brick arch; the question remains whether it should be injected under pressure or could be induced by the vacuum produced by the exhaust nozzle.

All types of coal-dust firing have a higher internal consumption than grate firing. This means that the amount of energy that must be used up in the process of burning coal dust is greater. In grate locomotives, this internal consumption is generally about 8 percent of engine output. The earlier models of coal-dust locomotives had an internal consumption of about 12 percent, the 4-percent differential over the grate locomotives was needed for operation of the blowers and mechanical stokers.

If internal consumption is to be covered only by the exhaust nozzle, it must be remembered that the efficiency of an ejector (and the exhaust nozzle must be considered an ejector) is only about one fifth that of a blower. The locomotives now operating on induced draft have an internal consumption of about 20 percent of maximum boiler output, and this still does not give an adequate air excess. It should be said that, in principle, an air excess of 1.3 at maximum load must be maintained when firing coal dust to assure the complete combustion of all fuel particles. It is clear that a shortage of air must occur during combustion.

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To avoid this, the air velocity would have to reach 70 meters per second. This can only be attained by further increasing the degree of the vacuum in the firing, that is, in the smokebox. But this would make the vacuum so great that it would probably take a considerable part of the boiler output to maintain it. It is not, however, the purpose of coal-dust-firing equipment to burn the fuel merely to meet its own internal consumption.

The earlier design of coal-dust locomotives had proved quite satisfactory. This design made it possible to fire even high-ash brown coal with good results. Of course, it still had a few faults which, however, are relatively easy to correct; thus, for instance, the long worm-conveyer stokers frequently caused difficulties. Stationary boiler design construction has also largely abandoned the worm-feed stoker, and replaced it with the trouble-free bucket-wheel stoker.

To sum up, the coal-dust locomotive has passed its test, and when more fully developed, it will represent a substantial factor in increasing the economy of locomotive operation. Proper improvement in design can render it capable of replacing black coal entirely and of operating with substantially greater savings than the grate locomotives now burning briquettes.(3)

SOURCES

1. Die Kohlenstaublokomotive (The Coal-Dust Locomotive), by Hans Wendler, Der Verkehr, Vol V, No 5, May 1951

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3. Die staubgefeuerte Lokomotive (The Dust-fired Locomotive), by Hermann Koppe, Bergbau und Energiewirtschaft, Vol IV, No 4, Apr 1951

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